

LUNAR PRODUCTION AND APPLICATION OF SOLAR CELLS,
AND SYNTHESIS OF DIAMOND FILM

Final Report

NASA/ASEE Summer Faculty Fellowship Program--1991

Johnson Space Center

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Date Submitted:	August 9, 1991
Contract Number:	NGT-44-001-800

ABSTRACT

This report will describe two projects which are carried out under the Summer Faculty Fellowship Program-1991:

I. A conceptual design of a solar cell manufacturing plant on a lunar base. This is a large program that requires a continuous and expanded effort and the present report will reflect a current status.

II. An experiment on the synthesis of diamond film. Encouraging, but not yet conclusive evidence has been obtained on a new method to synthesize diamond film. The procedures and observations are presented in this report.

A third project is an analysis of the solar cell performance over five years on the moon based on Apollo missions. A paper has been completed and will be submitted to the journal Solar Cells for publication. The paper is co-authored with J. R. Bates of JSC who carried out the experiment and collected the data about twenty years ago. Due to the page number constraint of this report, this paper will not be included but will be available separately.

Following is a table of contents:	pages
I. A Solar Cell Production Plant on Lunar Base	2
1) Solar Cell Components and Processing	2-6
2) Production Plan	6-8
3) Systems Engineering	8-9
4) Conclusion and Recommendation	9-10
5) References	11
II. An Experiment on a Possible Diamond Growth Method	12-14

A Solar Cell Production Plant at a Lunar Base

Introduction

Electric power is a requirement for lunar exploration. One method to produce this power is through a conversion of solar energy by a photo-voltaic device known as a solar cell. A good example is the solar cell panel of the seismic experiment of the 1969 Apollo 11 mission. The total power level of these panels was about 40 watts. Since that time, there has been much progress in solar cell technology and larger scale solar cell panels have been realized. Multi-kilowatt solar panels have powered satellites and several megawatt power solar panels have been constructed for terrestrial operations.

Through the analysis of rocks and soil retrieved from the moon, it has been recognized that the materials required for fabrication of solar cells can be provided by materials indigenous to the moon¹. A solar cell production process based on vacuum and heat, both of which are naturally provided by the lunar ambient can be envisioned. Thus in addition to an indigenous material utilization, an indigenous environment utilization can be realized. This approach would greatly reduce the reliance on Earth resources which would have to be transported to the lunar site.

1) Solar Cell Components and Processing

The solar cell adapted in the present development is based on a thin silicon film. As a thin film, a support structure in the form of substrate is required. The physical aspect of the silicon component and the substrate has been discussed previously². The present report will be devoted to the production aspect.

(i) Substrate.--There are various kinds of substrate which can be used to make solar cells. They are listed in the following table:

<u>Substrate</u>	<u>Lunar source</u>	<u>Fragility</u>	<u>Production Facility</u>	<u>Production Mode</u>
silicate glass	Available	Fragile	Complex	batch process
iron, titanium or steel	Available	Stable	Complex	continuous process
polyimide	Not available	Stable	Complex	continuous process
metallic glass	Available	Stable	Simple	continuous process

In terrestrial application, silicate glass, steel and polyimide have been used. For the lunar case, other materials listed above can also be considered due to the absence of corrosion elements. One deciding factor on the choice of the substrate would be the lunar availability. In this case, polyimide would not be practical because of the lack of starting material. Another point of consideration is based on a production schedule: If solar cells are to be made before a capability of lunar industry to produce the substrate exists, and the substrate has to be transported from the earth, glass would not be a practical choice both because of its fragility and weight. For this analysis, suffice that the solar cell fabrication is not greatly dependent on the specific types of the substrate.

(ii) Silicon Layers.--The semiconductor silicon layers, either in amorphous or microcrystalline form, are to be deposited from the vapor of molten-silicon heated in a vacuum. The preparation of the silicon layers has been described previously², the production procedure will be described under the production plan

(iii) Hydrogenation.--Thin film silicon solar cells, including amorphous silicon and microcrystal silicon, require hydrogen passivation of the inherent defects. In the conventional chemical vapor deposition, the starting silicon material is a hydride and contains rich

hydrogen component. Thus the hydrogenation is accomplished in situ during the silicon deposition. The power output of solar cells made by this process shows a deterioration of about one third after the first month of operation under solar illumination and a somewhat slower decay afterwards. This instability is explained by a formation of polymers of SiH_2 due to an excessive hydrogen content in the deposition process³. The formation of this polymer is greatly reduced in a two step process adapted in the present approach of a deposition of silicon first by evaporation and followed by a post hydrogenation. The hydrogenation involves annealing the deposited material in a hydrogen plasma at about 300°C . In the current laboratory practice, hydrogen flows continuously at a pressure of approximately of 1 torr. At a lunar base, hydrogen will be scarce and conservation is highly desirable. A method to achieve this purpose is to replace the continuous hydrogen flow with a stagnant operation where the system is closed with only a limited hydrogen replenishment to compensate for the hydrogen diffused into the silicon body. Such an operation is not possible in the chemical vapor deposition system since, in that case, besides the silicon hydride, an amount of doping impurity is removed. The relative concentration, which should be maintained at a constant value, would vary due to the different removal rate of the dopant and of silicon. However, in the present approach, there is only a single hydrogen component and thus a stagnant operation becomes possible. A laboratory experiment to confirm this approach would enhance the practicality and the economy of the lunar production process.

(iv) Electrode Formation.--Depending on the detailed solar cell structure, the electrode material would be different. In the case of a combination of a top microcrystal layer on the amorphous layer, due to an adequate electrical conductivity of the microcrystal silicon, a grid electrode configuration can be applied. Two electrode materials which would be suitable for lunar solar cells are aluminum and titanium. These materials are easily oxidized and become

electrically resistive in the terrestrial environment. The oxidation problem does not occur under the lunar vacuum condition.

A different case is that when the solar cell is made completely of amorphous silicon, a large area coverage instead of discrete grid lines becomes necessary. In this case, the electrode material has to be both optically transparent and electrically conductive. Oxides of several metals such as indium, tin or zinc satisfy these requirements, but these metals are rare in the lunar rocks.

The electrodes described above are for the top electrode where the light enters. The bottom electrode can be the substrate itself when the substrate is conductive. In this case, a solar cell with a large area would provide large electrical current but the voltage would be limited to about one volt. To produce a high voltage, the large area has to be dissected and reconnected in series. A means to make this connection is by two pairs of terminal clamps such that the terminals of one pair is connected to the top of one cell and the bottom of the second cell, and vice versa for the second pair. The clamps will be designed such that the connections can be made mechanically and robotically.

A different situation is that when the substrate is not conductive. In this case, solar cells can be a continuous large sheet and the electrode patterns, with a combination of series and parallel connections can be deposited on the substrate as well as on the top surface of the solar cell.

2) Production Planning

Two schemes of the production plant can be considered, a full production plant and a smaller pilot production plant. The full production plant, with an annual solar cell production rate of multi-megawatt powers can be realized based on an extrapolation from ensuing discussions. The present report will devote to

a pilot plant in order to acquire a operational experience and facilitate an earlier realization of the lunar solar cell production.

Processing chambers of this pilot plant will consist of three independent modules:

i) Silicon deposition chamber.--There are three or possibly four different silicon layers. These layers will be processed time sequentially in a single module. Inside the chamber, two different silicon crucibles will be placed, one for intrinsic silicon and one for p-type silicon alloyed with boron. N-type silicon can be made by a coevaporation of intrinsic silicon and antimony. In operation, a stepping mechanism will place the crucible with the different silicon types into the focal point of the concentrated light beam. In between successive depositions of different silicon layers a louver will be manipulated to block off the incoming light beam such that a stray deposition does not occur.

Finally, for the microcrystal silicon layer, the substrate temperature has to be modulated. One method to achieve this temperature is to adjust the louver of the substrate heater window to provide an elevated temperature of 550°C. This temperature would preclude many substrate materials. A lower temperature growth of microcrystals has been reported through a reactive chemical vapor deposition⁶. Whether this can also be realized in vacuum evaporation is yet to be investigated.

In order to reduce the large range of the tracking angle of the solar concentrators, which in practice would require multiple optical elements, restriction of the operation time would be helpful. In this case, instead of a whole 340 hours of lunar day, only a fraction of a lunar day will be operative. Take this fraction to be $\frac{2}{3}$, the time equivalent will be 227 hours and, the total production rate would be reduced. For a solar cell area of 0.1m^2 and a complete deposition time, including changing the silicon source, to be 0.5 hour, the total area of solar cells produced per a lunar day will be $0.1\text{m}^2 \times 227 \text{ hours} / 0.5 \text{ hour} = 45.4 \text{ m}^2$. Assuming

conservatively a solar cell conversion efficiency of 5%, the power output becomes $45.4\text{m}^2 \times 70 \text{ w/m}^2 = 3.2 \text{ KW}$. For an earth year, the total solar cells will produce 38 KW. This number almost coincides with the solar panel output of the Freedom Space Station under present design of 37 KW.

A distinct feature of this chamber is an absence of high voltage and high power leads. These leads are numerous in the common vacuum deposition chamber and the necessary electrical isolation takes up much space in the chamber. Our conceptual vacuum chamber would have a much simpler interior and the space utilization would be more efficient. However, there is also a problem which is less important in the ordinary system in which the window is merely a view port there. In our system, the window becomes the entrance port of the light beam as a power source and high transparency is of utmost importance. A technique to maintain a clean window would be an important subject.

b) Hydrogenation chamber.--While in the silicon deposition chamber, the substrate should be in the line of sight of the silicon source; therefore, multiple solar cells can not be stacked for simultaneous deposition. In the hydrogenation chamber, however, the solar cells can be stacked with a separation of about the mean free path of the plasma ions. At 1 torr pressure, the mean free path is on the order of 1 cm. The required temperature is about 300°C which will be obtained through solar heating.

The hydrogenation process requires about one hour², which is longer than the silicon deposition time. However, the output from silicon deposition chamber can be accumulated to batches, and the production can thus be streamlined.

c) Electrode attachment chamber.--This chamber will deposit electrode materials by a vacuum evaporation by solar heating with a masked grid or other desirable electrode configuration and the adapted metal or oxide materials.

3)Space System Engineering

The system involvement can be divided into several components:

(i) Material sources.--The two chief materials are silicon and metallic or glass substrate. Silicon extraction from lunar rock has been investigated in several contract reports^{7,8}. Further purification during the vacuum deposition can be made with the same principle of a fractional distillation.

At present, there is no specific effort on substrate construction. This can be carried out when the lunar solar cell production project is dedicated and the size of funding is adequately scaled.

(ii) Heater system.-- The basic component of the solar heater system are a set of optical lenses and mirrors. The present report only studies the general concept. Further effort with expertise is evidently necessary in order to build a real system.

(iii) Machinery.--Under this category is the control and monitoring system, the motor drive to manage the transfer of the substrate, the optical tracking system, and the interchange of the deposition materials. These systems, including robotic features, already exist in terrestrial industry and therefore an adaption of these systems will be basically a development process.

iv) Physical size, weight, and cost analysis --The physical size of the manufacturing plant, including components described in iii) above can be packed in a size of about 1 m³, and the weight would be sub-tons for a pilot plant. For production plant, the value would be less than one order magnitude higher.

For the cost, in earth industry, the chief cost is the plant facility and labor which represents 70%⁹. In the lunar case, these aspects are not applicable and the only direct cost would be that under iii). Cost of such systems may be in the range of several hundred thousand dollars when applied on earth. When these systems are to be employed on the moon, the

packaging and the reliability requirement could increase the cost by perhaps one order of magnitude.

4) Conclusion and Recommendation

I came to Johnson Space Center under the Summer Faculty Fellowship program with a background of solar cell technology and some planning to produce solar cells on the lunar base. Through the eleven weeks of concentrated study and intensive interaction with the scientists in this Center, in an environment where one sees the giant rocket on the entrance of the Center, pictures of the lunar surface and the astronauts on the hallway, and the real lunar rocks are almost adjacent to my office, my concepts are clarified and my conviction is deepened that the lunar base is a fertile ground to support a solar cell manufacturing: There are materials on the base which, after some processing, can be the components of the solar cell. The vacuum as a lunar ambient is a built-in resource for solar cell processing. The quality of the vacuum the earth laboratory can only envy. The Sun as a power source for solar cell deposition is available only half of the time, that is, during the lunar day, albeit cloudless and stable.

The basic idea of photovoltaic operation to convert solar energy into electricity on lunar base is as applicable as it is on Earth. However, there are some differences. One example is amplified through my recent work at JSC on the analysis of solar cell output data from several Apollo missions: due to the prolonged heating period with heat removal only through an inefficient black-body radiation, the solar cell temperature would be very high and the solar cell performance would be highly inefficient if one transferred directly the terrestrial solar cell structure to the lunar solar cells. An emphasis has to be paid on the emissivity and reflectivity of the solar cell even more stricter than the space solar cell-the heating period of space solar cells is much shorter than that of lunar cells.

The concept of solar cell processing I have developed has a built in simplicity that makes the process practical in necessarily restrictive lunar conditions. However, there are

numerous detailed steps to be experimented and established, some of these have been discussed in the body of the report. In consideration of technological and engineering effort involved in this project, it is high time to invest a concerted effort for this purpose.

I recommend that an implementation of a lunar solar cell manufacturing project should be carried out, involving both laboratory work and system planning, to correct the current unsatisfactory status of meager efforts of a few people. At present, opinions can be found in information media and the technology community as the positive encouragement on lunar and martian exploration, and solar cell manufacturing has been enumerated in a JSC document: Using Space Resources¹ and cumulated in Architecture IV of America at the Threshold¹⁰). I propose that steps should be taken commensurate with these two august documents.

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II. An Experiment on a Diamond Growth Method

In recent years, there has been a proliferation of activities to grow diamond, based on the decomposition of a gaseous hydrocarbon source as suggested thirty five years ago by B.V. Spitsyn and B.V. Derjaguin (USSR Inv. Cert. no. 339134, 1956). One deficiency of this method is that the diamond grown by this approach is confined to polycrystals of micron sizes. Crystals of millimeter or larger have been grown so far only on natural diamond faces by homo-epitaxy. A new method which potentially can grow large single crystals by carbon ion implantation on metals has been reported by Prins and Gaigher recently (Second International New Diamond Sci. and Tech. Conf. Sept., 1990 Crystal City, Va.). These metals should have a lattice matching to diamond and have a low carbon solubility. To overcome the disadvantage of using ion implantation as a means of introducing carbon, I have been working on a different approach based on a controlled diffusion of carbon through the same type of metals of Prins and Gaigher. In this method, a paste of an organic suspension of fine grain carbon black is painted on one side of the metal foil surface. By heating in a vacuum or in a protective atmosphere, carbon diffuses through the foil and resurfaces on the opposite surface. The carbon atoms, when they have sufficient mobility, could grow into diamond through a hetero-epitaxy with the host metal.

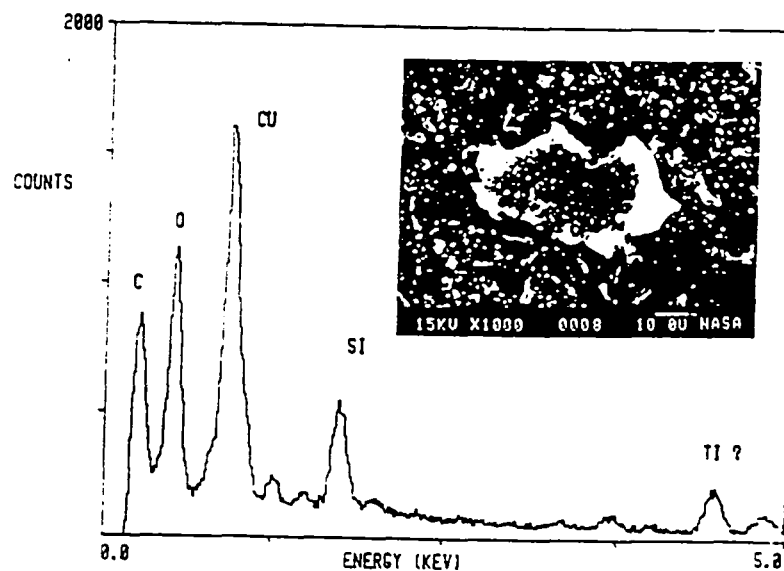
In my work prior to arrival at JSC, I have used vacuum ambient and some preliminary experiments have been made to determine desirable parameters, including the temperature and time window. After my arrival at JSC, I have found that there is a convenient facility in the form of a tube furnace with a controllable protective gas. In my previous vacuum arrangement, the metal in the form of foil strips was resistively heated by passing electrical current through the metal. The resulting temperature is highly non-uniform from near the electrodes to the mid-section. Furthermore, the temperature was measured by an optical

pyrometer. In the low temperature range used in the experiment, around 600 to 1000°C, there is a temperature uncertainty of around 50°C. With the use of a tube furnace, uniformity and accuracy evidently would be greatly improved.

In my previous arrangement for the protective gas, I used low pressure hydrogen in combination with a mechanical pump. At JSC, since there is a safety concern and a hydrogen removal system cannot be readily made, I have used argon at slightly above one atmosphere pressure (suggested by Amy Jurwitz.). In this case, the excess gas is passed through an oil bath to prevent an air backflow and the mechanical pump is eliminated.

I have carried out the experiment with some encouraging results:

1. The carbon diffusion through the metal foil and outdiffusion to the opposite foil surface has been confirmed by an energy dispersive spectrum analysis (EDX) shown in the following figure in combination with a scanning electron microscope (SEM) picture in the



inset. This specimen is made with the following conditions: The metal is a copper foil of 25 micrometer in thickness. After a purge with argon of 17 lbs pressure, namely, about three lbs. above the atmosphere pressure, for two hours, the temperature is raised to 925°C in half an hour and maintained at this temperature for six hours. After that heater power is turned off and the specimen is naturally cooled to about 60°C in three hours.

The EDX picture shows that, besides carbon and the substrate copper, there is a considerable amount of oxygen, silicon and possibly also titanium in the general area excluding the large pattern in the center of the inset SEM picture. While the large pattern is completely carbon according to EDX, the small bright specks are oxides of various metals and of silicon.

The pressure of oxygen is evidently undesirable as it would etch away the carbon, including the diamond crystal. This etching effect might explain an isolated occurrence of the large carbon patterns. An effective method to eliminate the oxygen would be to mix a small amount of hydrogen into the argon gas. This approach, suggested by G. Lofgren, can be carried out easily by pre mixing of the two gases, but the available time prevents this attempt and has to be awaited for a later time. Future effort will be directed towards the crystallographic and Raman scattering identification of the carbon specks such as the large central pattern in the inset. Once the diamond structure has been proved, the next objective would be a realization of an epitaxial growth such that the bright specks become a large area film coverage over the whole grain of the metal, eventually to a large single crystal. This plus a formation of the oxides is the original concept of this work.